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A LABORATORY MODEL OF AN INTEGRATED WATER RECOVERY SYSTEM

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FOREWORD

This report was prepared by General Dynamics/Electric Boat, Groton, Connecticut. The fabrication and testing on which this report is based were carried out under Contract AF 33(657)-9310, Project No. 6373, "Equipment for Life Support in Aerospace," and Task No. 637305, "Life Support Accommodations, Integration, and Analysis." This work was monitored by Mr. A. B. Hearld, Biotechnology Division, Biomedical Laboratory, 6570th Aerospace Medical Research Laboratories, Wright-Patterson Air Force Base, Ohio. Work under this contract was started in June 1962 and was completed in May 1963.

This integrated water recovery system was designed by General Dynamics/Electric Boat, Groton, Connecticut.

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ABSTRACT

This study was conducted to construct and test a laboratory model of an Integrated Water Recovery System. The system was designed to convert to potable water 4.2 liters of urine plus 5.0 liters of wash water daily, under weightless conditions. It consists of a vapor compression distillation still, a post-filtration system, waste water and potable water storage tanks, a hot and cold water dispensing unit, and a graphic display control panel. This system produces potable water at the approximate design capacity under weightless conditions.

PUBLICATION REVIEW

This technical documentary report is approved.

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INTRODUCTION

A design study (References 1 and 2) was made by General Dynamics/Electric Boat for an integrated water recovery system capable of converting to potable water 4.2 liters of urine plus 5.0 liters of wash water daily. The system evolved from this study is capable of storing urine and wash water; converting the urine and wash water to potable water by a vapor compression distillation cycle, followed by activated carbon and bacterial filtration; dispensing hot and cold potable water at the specified rates; and storing the potable water.

The object of this program is to fabricate the system designed and to operate the system to ascertain its operational capability.

SYSTEM REQUIREMENTS AND DESIGN BASIS

The requirements of the system and the basis used for designing the system are as follows:

1. The system shall be in accordance with the design study (References 1 and 2).

2. The system shall be capable of converting to potable water by vapor compression distillation 4.2 liters of urine and 5.0 liters of wash water daily.

3. The system shall be capable of storing waste water and potable water, and of dispensing hot and cold potable water.

4. Operation in a condition of weightlessness (hypothetical) shall be possible.

5. Capable of operation while exposed to:

   a) temperatures of 60 - 75°F

   b) pressures of 7.35 - 12 psia

   c) relative humidity of 30 - 50%

6. The evaporation-condensation will be carried out at approximately 5 psia with a pressure rise across the compressor of 0.5 psi.

7. Storage tank capacity of 2-1/2 ± 1/16 gallons of water with the waste water tank capable of collecting, storing, and automatically transferring the waste water to the recovery unit, and with the potable water tank capable of receiving water from the recovery unit, maintaining this water at a positive pressure for dispensing, and receiving water from an external source prior to launch or during flight.

8. Hot water delivered at temperatures of 170°F ± 10°F with an automatic shut off if the hot water exceeds 195°F. The hot water will be delivered at a maximum rate of 3 pints every 2 hours at the specified temperatures either all at one time or in smaller portions.

9. The system shall have a dispensing unit located 5 feet (minimum) from the water heater. The dispensing unit shall consist of a cold water tap and a hot water tap, each identified and mounted side-by-side in a sunken panel. Each tap shall be designed for injecting water into a Weber Webcor Space Feeding Tube.

10. Hot water heater will withstand pressures of 1 to 5 psig.

11. Instrumentation and controls to maintain pressures, temperatures, flow rates, etc., required for efficient and automatic operation, shall be provided.

12. Materials used will be corrosion resistant when exposed to urine or wash water, will be nontoxic and nonirritating in a closed environment, and will not impart a disagreeable taste to the recovered water.

13. The system will be housed in a lightweight console designed for mounting on the floor of a cylinder having an inner diameter of 7-1/2 feet, the floor being 40 inches from the longitudinal axis of the cylinder. The console shall be placed against the cylinder so as to leave a 33-inch wide aisle centered along the length of the floor. Operating controls will be mounted on the outside of the console.

14. The system shall be easily dismantled for cleaning, replacement of parts and filters, and general maintenance.

15. The system shall be designed to operate on a 28-volt, d-c power supply.

DESCRIPTION OF EQUIPMENT

GENERAL

The integrated water recovery system is designed to recover the daily water requirements of 3 men from urine and wash water under weightless conditions without the use of auxiliary equipment. Overall views of the system are shown in Figures 1a, 1b, and 1c. The total weight of the system, including the mounting frame, is 170 lbs. It should be noted that the system was designed to fit inside of a 7-1/2 ft diameter cylinder; the bottom of the frame was left open to be available for other purposes, e.g., storage of feces.

Figure 2 is a flow diagram showing the relationship of the components within the system. The urine and wash water are introduced into the waste water storage tank through a polypropylene valve. A solenoid valve meters the waste water from the storage tank through a detritus filter and through the heat economizer and the second stage feed heater into the rotating evaporator. The feed is heated in the heat economizer by the hot effluent condensate and in the second stage heater by the superheat from the compressed vapor. The liquid thus enters the evaporator near its boiling point. The heat of vaporization is supplied to the liquid in the rotating evaporator-condenser by the compressed vapor condensing on the outside surface of the evaporator-condenser and by a make-up radiant heater.

The vapor from the evaporator is compressed whereby both its pressure and temperature are increased. Any superheat in this compressed vapor is removed in the second stage feed heater and it enters the condenser area at or near its saturation temperature. This saturated vapor is condensed on the outer surface of the rotating evaporator-condenser. The condensate is collected at the apex of the condenser area shell (under weightless conditions circular motion of the vapor creates a centrifugal force that holds the condensate against the outer shell). The noncondensable gases present are drawn off through the vacuum vent.

The condensate is drawn from the condenser area through the heat economizer by the condensate pump and pumped through a charcoal-ion exchange resin-bacterial filter into the potable water storage tank.

The potable water in the storage tank is kept under approximately 1-psig positive pressure, thus it can be drawn off readily at the cold water tap. The hot water tap has an auxiliary recirculating line operated by a hand pump which ensures constant temperature water throughout the line.

The feed solenoid valve is controlled by a sequence timer and by a level switch in the evaporator. When the liquid level

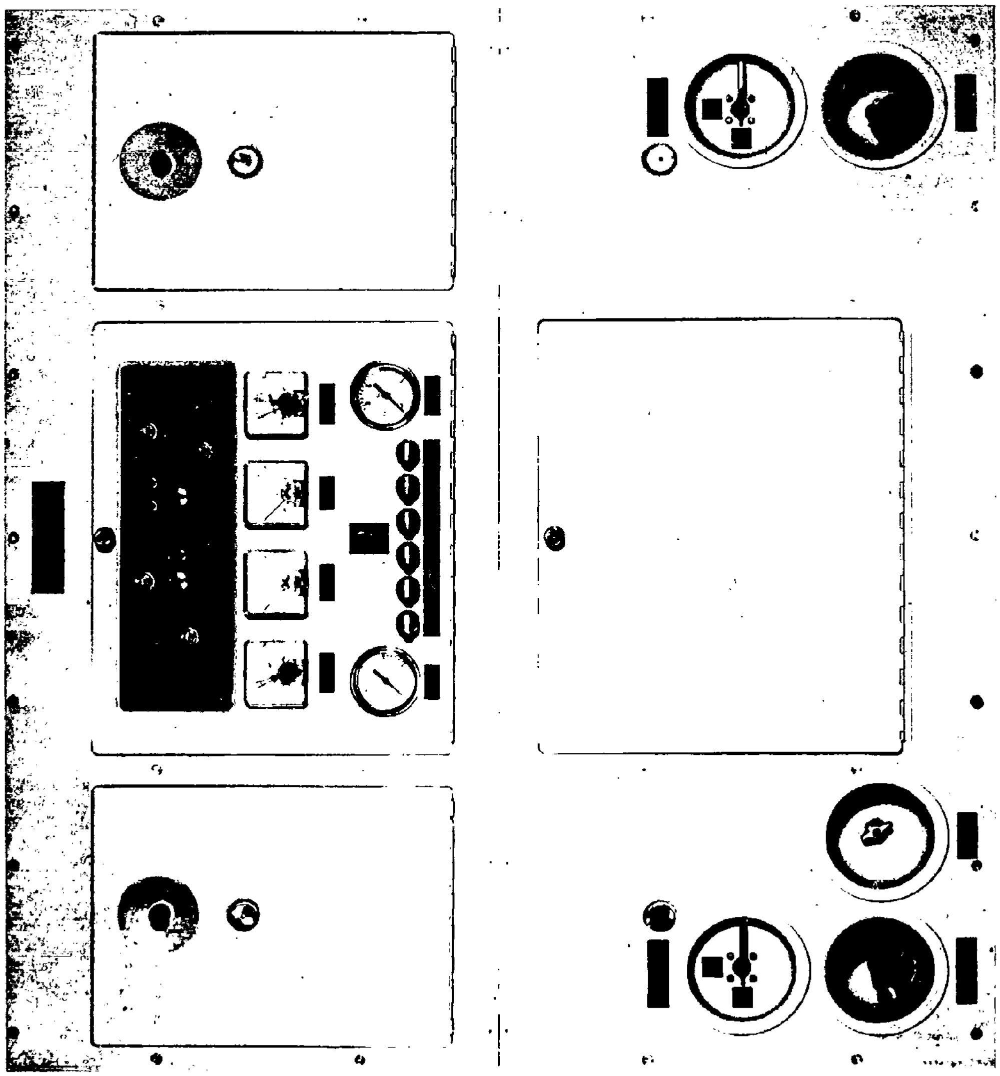


FIGURE 1a FRONT VIEW OF SYSTEM

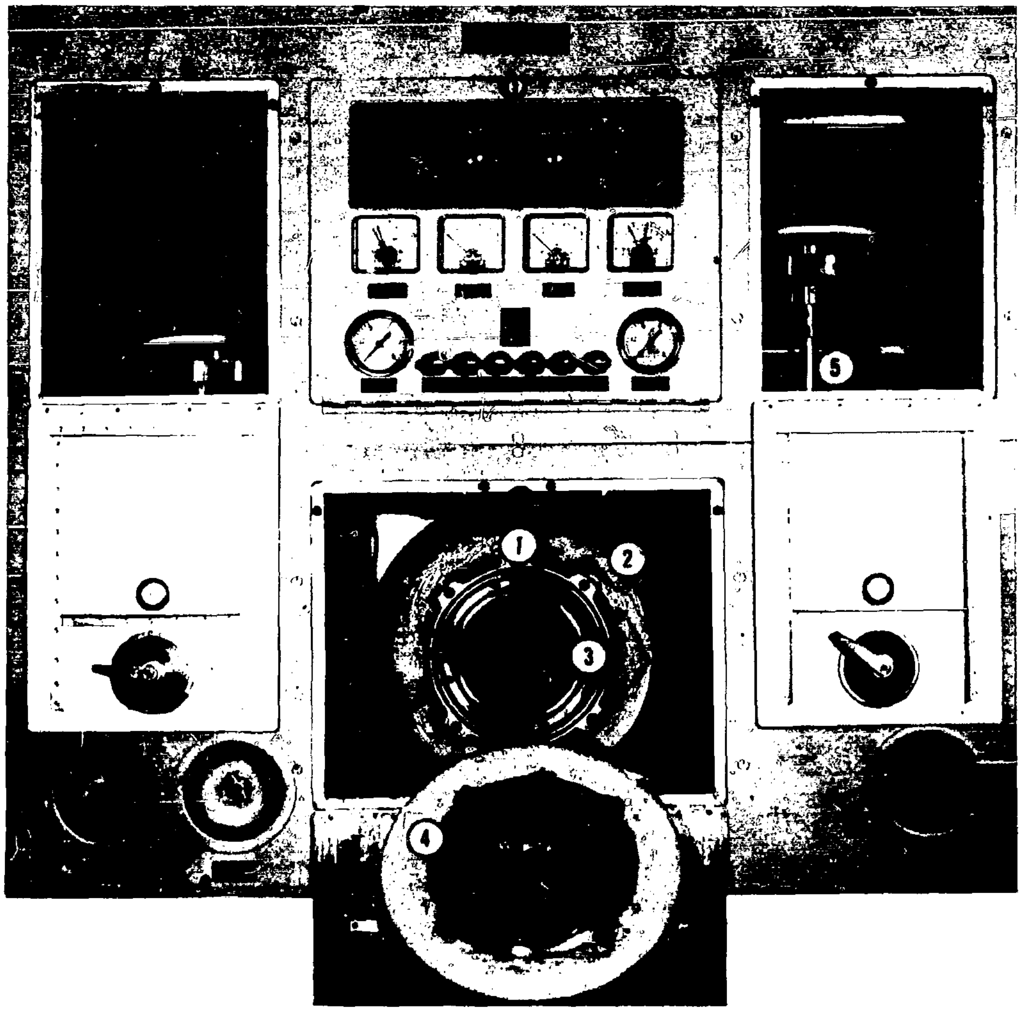


FIGURE 1b FRONT VIEW OF SYSTEM (OPENED)

1. Condenser area shell.
2. Polyurethane foam insulation.
3. Rotating evaporator condenser.
4. Front cover.
5. Waste water storage piston shaft.

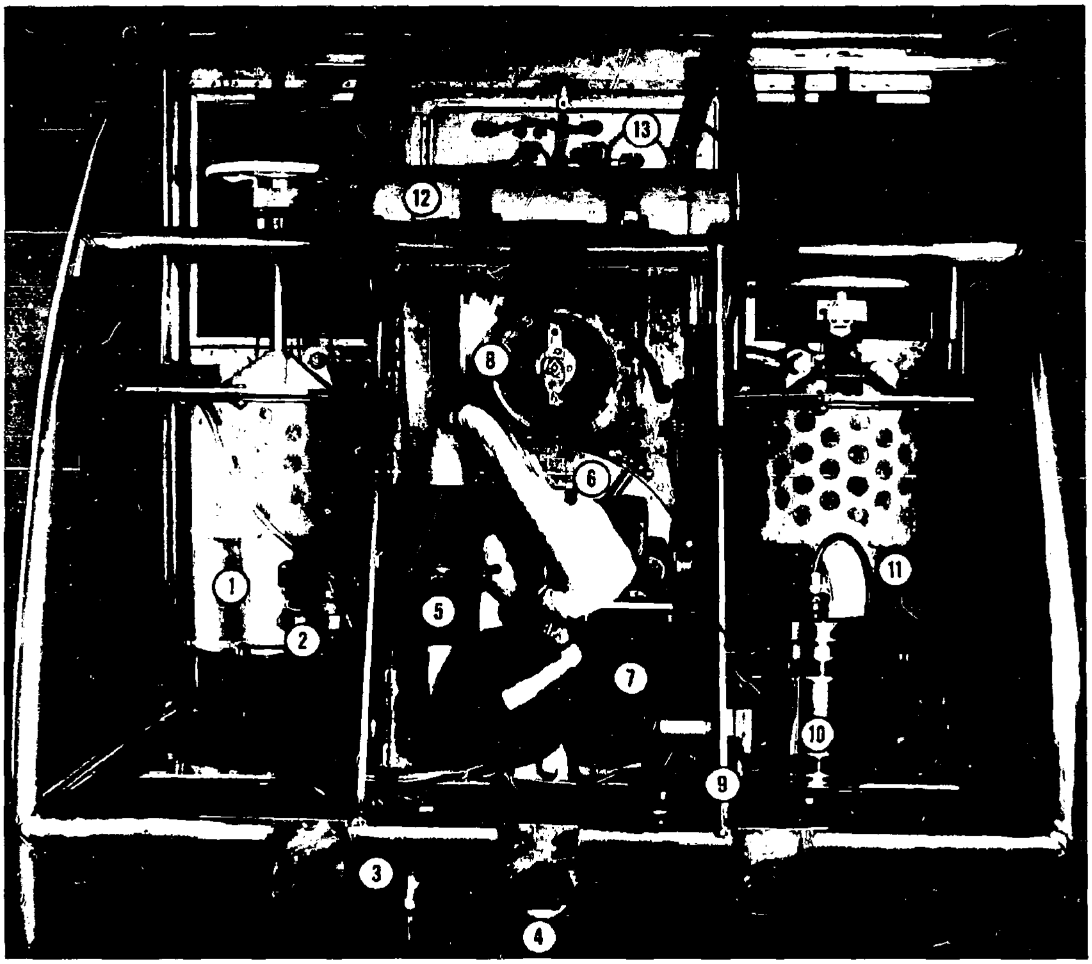


FIGURE 1c REAR VIEW OF SYSTEM

1. Waste water storage tank.
2. Detritus filter.
3. Feed metering valve.
4. Heat economizer.
5. Second stage heat exchanger.
6. Vapor compressor and gear box.
7. Compressor drive motor.
8. Speed control rheostat.
9. Condensate pump.
10. Condensate filter.
11. Potable water storage tank.
12. Hot water heater.
13. Rear of graphic control panel.

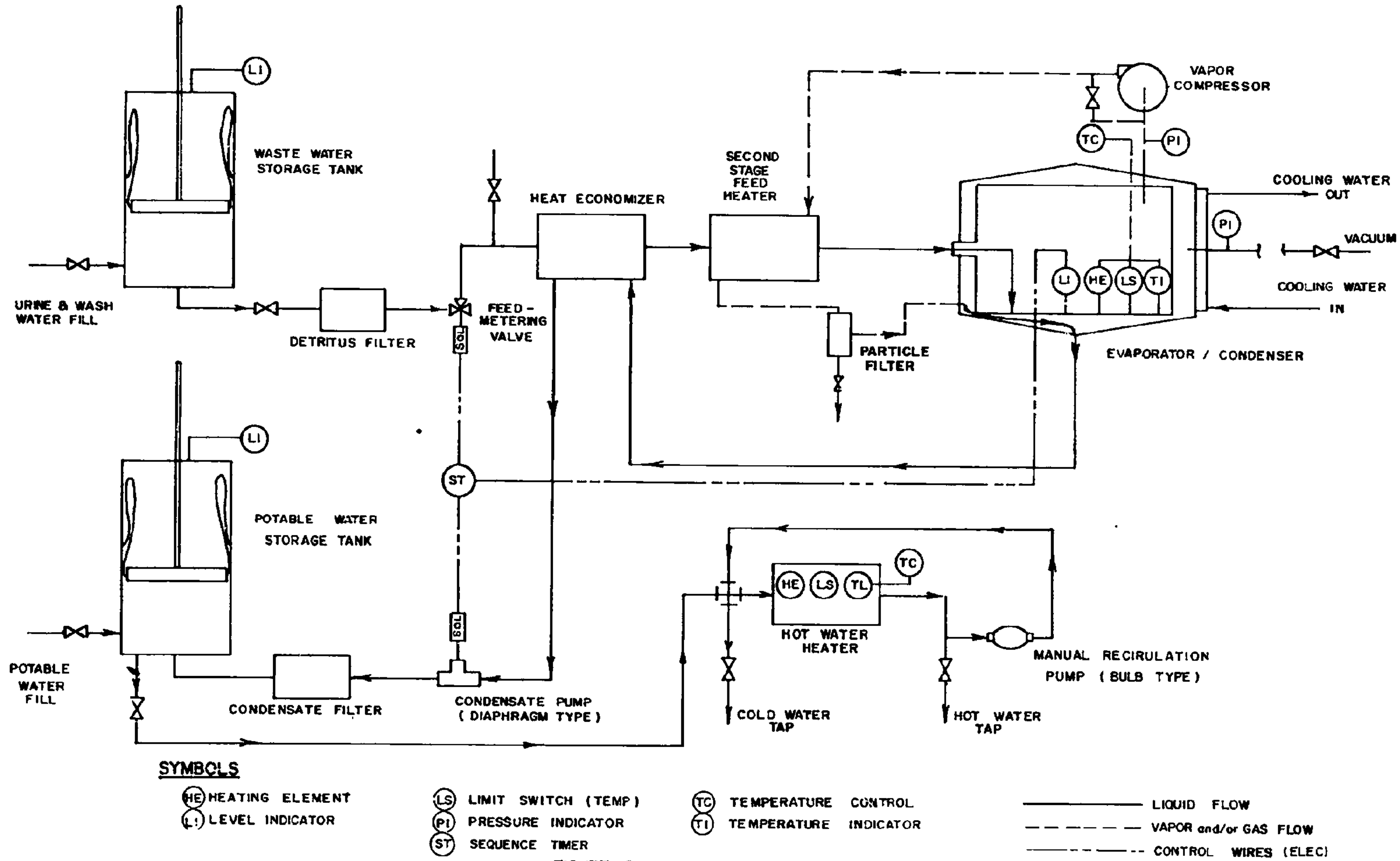


FIGURE 2

SCHEMATIC FLOW DIAGRAM
INTEGRATED WATER RECOVERY SYSTEM

is satisfactory, the sequence timer actuates the feed valve at a preset rate; when the liquid level becomes too high, the level switch turns the feed valve off. The condensate pump is also controlled by the same sequence timer.

The make-up radiant heater in the evaporator and the hot water heater are both thermostatically controlled - the radiant heater, by a thermocouple in the evaporating liquid; the hot water heater, by a thermocouple in the hot water tank.

WASTE WATER STORAGE TANK

The waste water storage tank is a cylindrical vessel 7-3/4 inches ID and 19 inches high. The tank is equipped with a rolling diaphragm attached to a movable piston thus giving a variable volume ranging from 0 to 8.1 liters (maximum). The piston has a full travel of 11 inches. Liquid in the tank is held under approximately a 1/2-psig positive pressure by two constant tension springs attached to the piston shaft. The internal liquid chamber is fabricated from stainless steel, while those parts that do not contact the waste water are fabricated from aluminim. The tank is fitted with two male ports at the bottom, one leads to a 1/8-inch polypropylene ball valve for adding waste water to the tank, the other connects to the feed metering valve.

The tank is equipped with a device for neutralizing the constant tension spring pressure to facilitate the introduction of liquid. This device consists of a stationary threaded rod around which the piston shaft moves. A lock ring attached to a threaded wheel engages the upper end of the piston shaft. The pressure is neutralized by engaging the lock ring onto the piston shaft and taking up on the wheel.

POTABLE WATER STORAGE TANK

The potable water storage tank is similar to the waste water storage tank with the following differences:

1. The liquid in the tank is held under approximately 1-psig positive pressure by four springs.

2. Parts in contact with water are anodized aluminum.

3. The tank is fitted with three male ports at the bottom, the first for adding external potable water to the tank, the second for adding the recovered water from the condensate pump, and the third for withdrawal of potable water for use.

Figure 3 shows the components of the storage tanks.

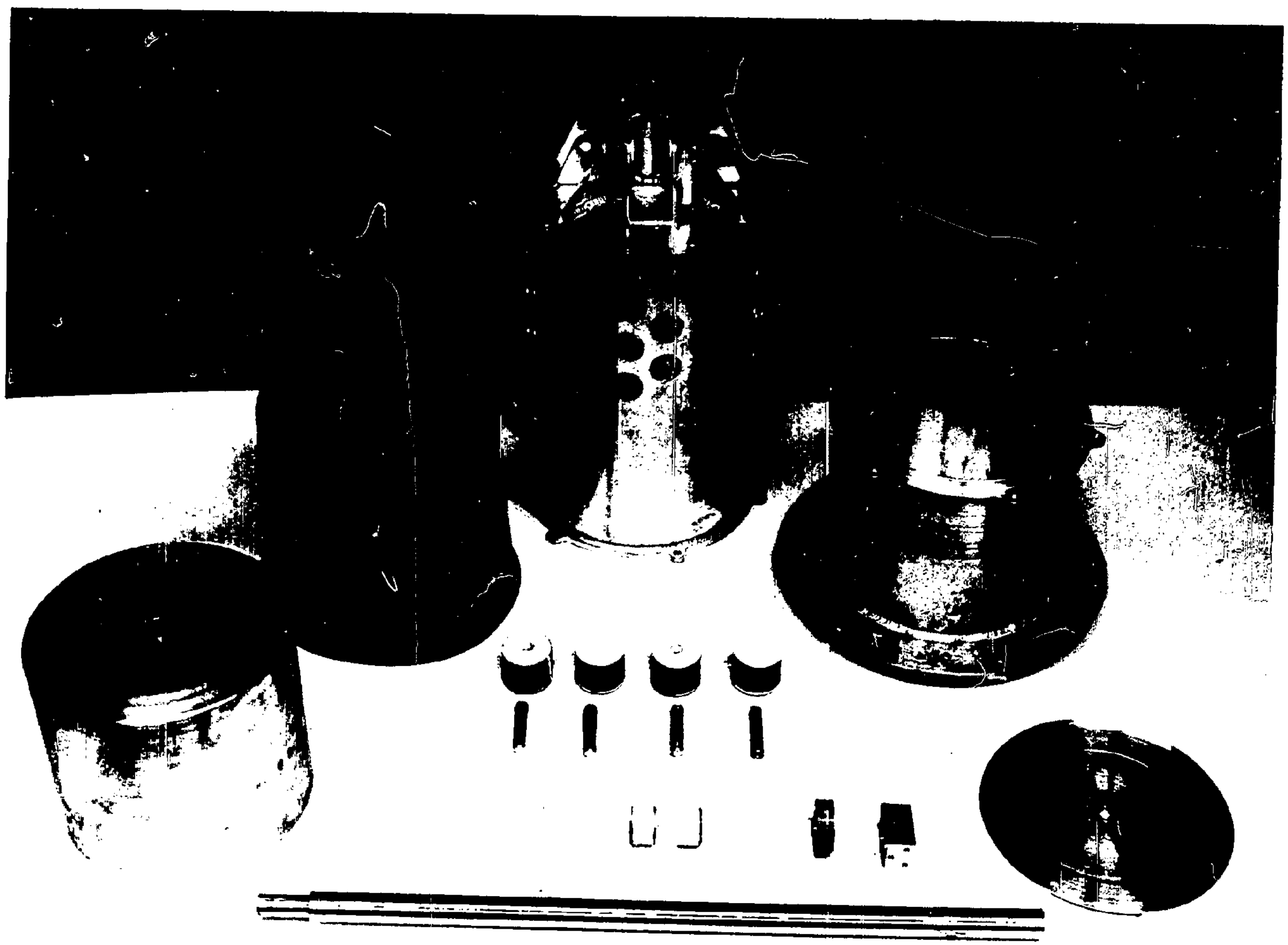


FIGURE 3 STORAGE TANK COMPONENTS

EVAPORATOR-CONDENSER

The evaporator-condenser is a cylinder 6-1/4 inches ID and 8-5/16 inches long, fabricated from 1/8-inch aluminum (Figure 4). One end of the cylinder is mounted on a 2-inch hollow shaft, concentric with the cylinder; the other end is fitted with a removable cover sealed with an O-ring. This cylinder rotates at approximately 175 rpm during operation. A stationary shaft is mounted through the hollow shaft. This shaft contains the liquid feed line, the vapor removal line, instrumentation and electrical lines, and mounts the radiant heater.

The (3/32-inch ID) liquid feed line is mounted perpendicular to the axis of the evaporator at the 6 o'clock position, midway along the axis. The liquid level sensor is a pointed carbon rod located 1/4 inch from the evaporator surface at the 6 o'clock position. The level sensor is moulded in a common removable instrumentation mount along with the heater-controlling temperature probes.

The radiant heater is mounted on the center shaft at the 9 o'clock position. The heater is a U-shaped rod with the legs of the U running parallel to the axis of the cylinder. Each leg of the U is 6 inches long. The heater has an operating power consumption of 300 watts.

The entire assembly is inclosed in a stationary aluminum shell 11 inches long, 7-11/32 inches ID at the ends, and 10-1/2 inches at the midpoint. This shell is in turn insulated with 2 inches of Freon-blown polyurethane foam. The concentric stationary and rotating drive shafts for the evaporator-condenser enter through the rear of this shell. These are sealed by neoprene lip seals. The front of the shell is sealed from the ambient by a hollow aluminum cover and an O-ring. It is locked in place with four 1/4-turn quick-opening fasteners and is insulated with 2 inches of polyurethane foam. The vacuum vent line is located at the center of this front cover. The evaporator is periodically cleaned of residue by a cleaning assembly.

CLEANING ASSEMBLY

The cleaning assembly (Figure 5) consists of a separate cleaning cover with a cylindrical cleaning element attached to it. The cleaning cover is held in place with five quick-opening 1/4-turn fasteners. The cylindrical cleaning element is made of coarse wire mesh with a perforated suction line running down the center. The assembly is indexed radially and axially in order to produce fresh cleaning surface and to cover the entire evaporating surface. The wire mesh is attached to the suction line by a cap screw enabling periodic replacement of the cleaning elements.

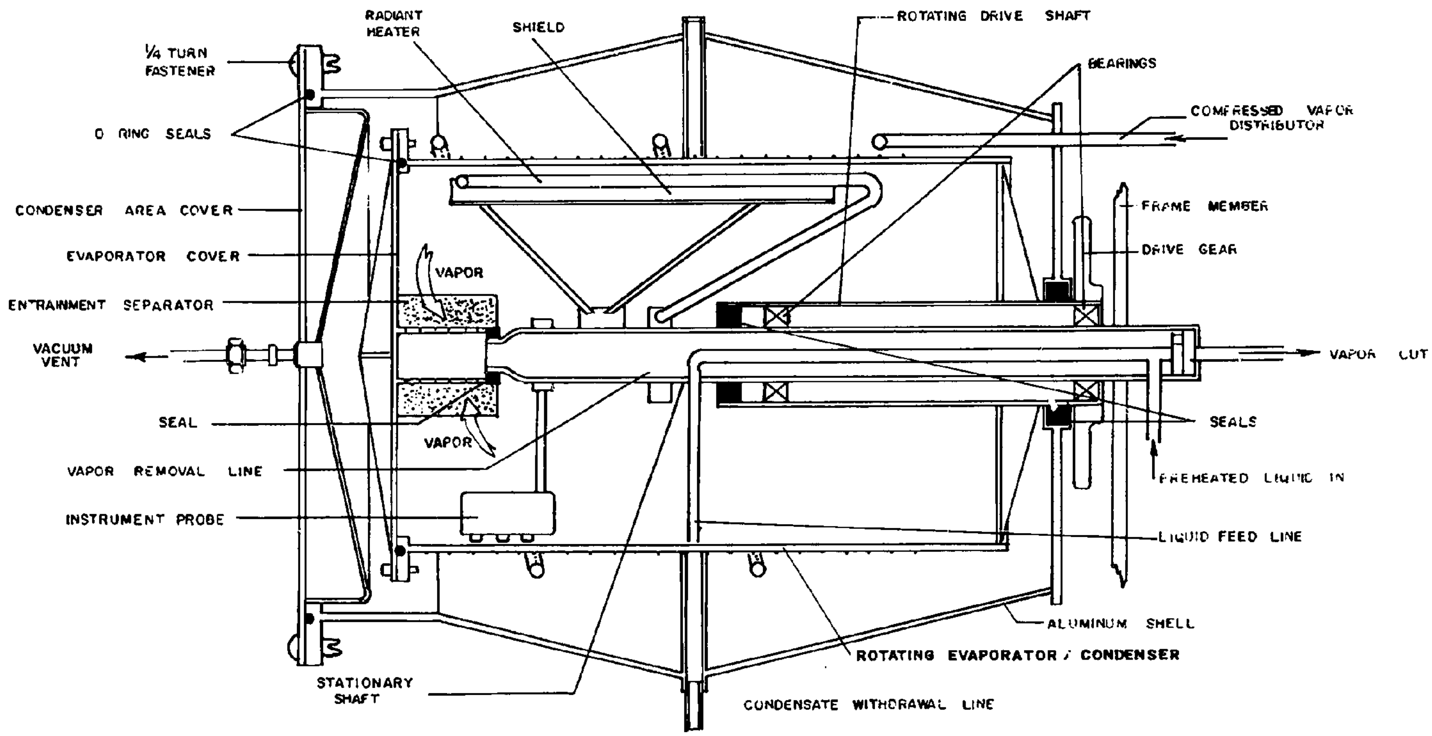


FIGURE 4

SECTION OF EVAPORATOR / CONDENSER ASSEMBLY
(HEATER SHOWN 90° OUT OF POSITION)

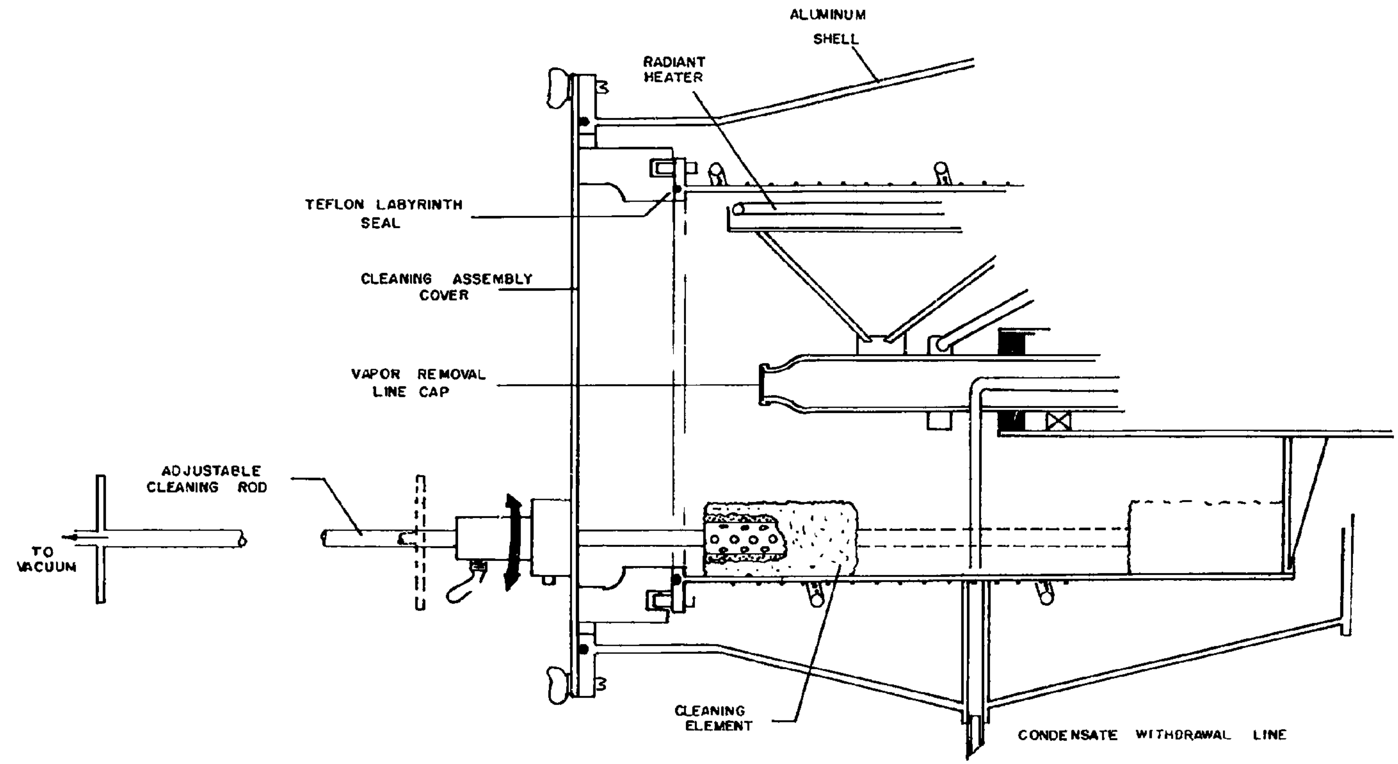


FIGURE 5

SECTION OF EVAPORATOR / CONDENSER ASSEMBLY
WITH CLEANING ASSEMBLY IN PLACE
(CLEANING ASSEMBLY SHOWN 180° OUT OF POSITION)

VAPOR COMPRESSOR

The vapor compressor is of the rotary vane type with spring-loaded Fluorosint blades; the compressor body is lined with a stainless steel sleeve and Teflon ends. It is driven at 1080 rpm by a gear reduction system which drives the rotating evaporator-condenser. The gear system is powered by a 1/2-hp 28-volt, d-c, 5500-rpm series wound motor. At this speed, the compressor has a capacity of 1.6 cfm of vapor at system pressure and a ΔP of 0.5 psi. The compressor has an overall size of 3-5/8 inch diameter and 2-3/4 inch length (excluding the drive shaft). The drive motor is 7-1/64 inches long and has a diameter of 3-1/2 inches (excluding the connectors). Figure 6 shows the components of the compressor and drive assembly.

FEED METERING VALVE

The feed metering valve works as a positive displacement pump consisting of a 3-port, 2-way solenoid valve and a constant volume collapsible liquid chamber. The solenoid valve is a 28-volt, 3/8-inch nylon body valve. The liquid chamber consists of a 10-inch length of 1/8-inch ID rubber tubing and a pinch clamp.

When the solenoid valve is energized, liquid from the storage tank fills the liquid chamber. When the valve is deenergized the ambient pressure collapses the liquid chamber forcing the liquid into the evaporator. The solenoid is pulsed at fixed intervals by the sequence timer and the feed rate is adjusted by changing the volume of the liquid chamber. The volume of the chamber is pre-set by moving the pinch clamp along the length of the tubing.

CONDENSATE PUMP

The condensate pump is a positive displacement feed pump consisting of a molded rubber diaphragm actuated by a solenoid, electrically sequenced to give a fixed flow rate slightly greater than the feed rate. Both ports of the pump are fitted with check valves. Figure 7 shows the components of the condensate pump.

URINE AND DISTILLATE FILTERS

Before the urine enters the evaporator, it is passed through a detritus filter, and the distillate, before it enters the storage tank, is passed through an activated carbon-ion exchange resin-bacterial filter. The filters can be seen in Figure 1c.

The urine filter housing is fabricated of polyvinyl chloride and is 3-1/2 inches in diameter and 4-1/2 inches long (outside dimensions). The housing is composed of three elements: a cylindrical body, a fixed bottom, and a removable cover. The bottom is sealed to the cylindrical bottom with epoxy resin; the cover, by an O-ring seal. The cover is held in place by a through bolt at

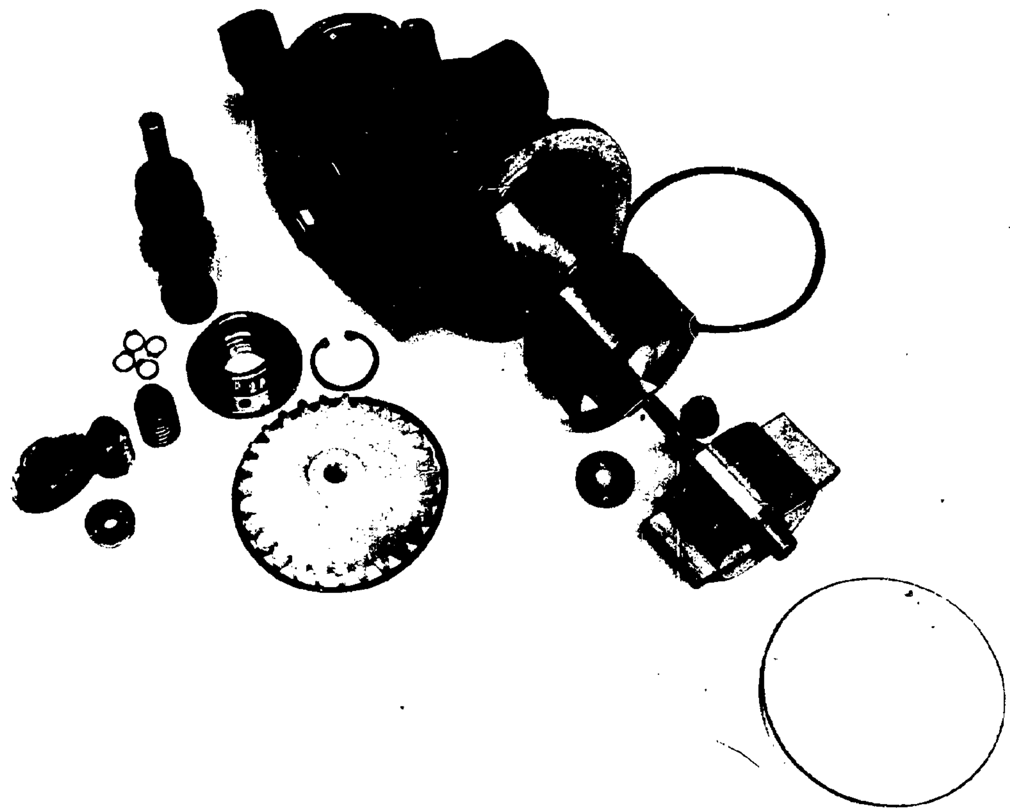


FIGURE 6 COMPRESSOR AND SPEED REDUCER COMPONENTS

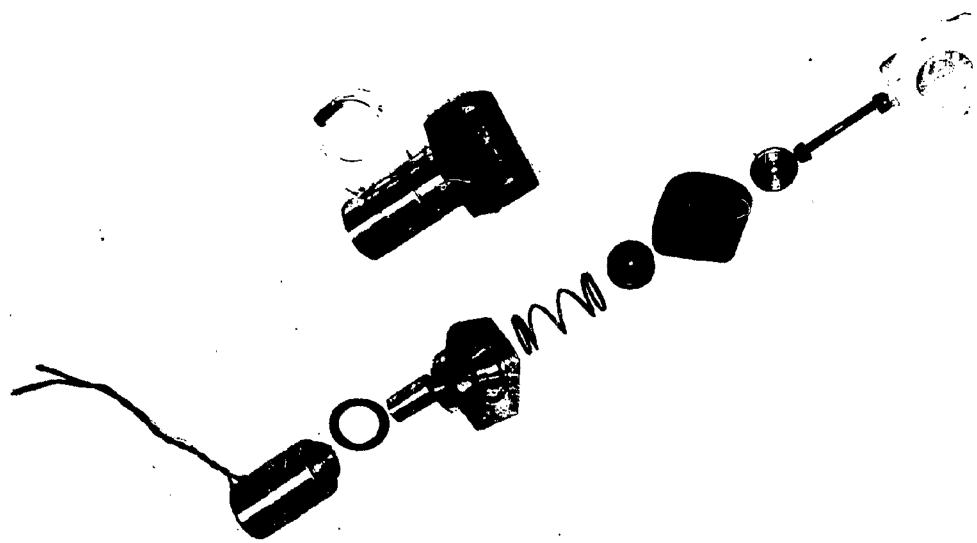


FIGURE 7 CONDENSATE PUMP

the center that threads into a captive nut in the bottom section. The cover and bolt also hold the removable acetate filter element in place.

The condensate filter housing is fabricated of aluminum and is 5-3/8 inches in diameter and 7-7/16 inches long (outside dimensions). The cylindrical housing has a threaded cover, sealed by a neoprene O-ring. The cover is locked in place with a set screw. The first 80% of the filter medium is composed of type KE-1 activated charcoal and the remaining 20% consists of mixed ion-exchange resin. The charcoal and ion-exchange resin are topped by a stainless steel wire mesh enclosed bacterial filter (0.45μ). The filter media is supported at the bottom (inlet) by stainless steel wire mesh and nylon felt.

HEAT EXCHANGERS

Heat Economizer

The heat economizer is a liquid-to-liquid counter-current heat exchanger consisting of two concentric aluminum tubes. The inner tube is 3/16-inch OD and the outer tube is 3/8-inch OD. The two tubes are joined by a helical wound ribbon. The assembly is 12-1/2 inches long and is enclosed in a 1-inch layer of Freon-blown polyurethane foam for insulation.

Second Stage Feed Heater

This liquid preheater is a liquid-to-vapor counter-current heat exchanger consisting of a coiled aluminum tube in a cylindrical aluminum housing. The liquid passes through the inside of the aluminum coil and the vapor on the outside. This coil is made from 1/4-inch OD tubing and has 12 coils of a 1-inch diameter. The cylindrical housing is 2 inches in diameter and 5 inches long. The assembly is insulated with 1/2 inch of plastic-rubber foam.

HOT WATER HEATER

The hot water heater consists of an immersion heater located in the inner tube of two aluminum concentric tubes. The outer surface of the inner tube is finned with 11 perforated aluminum radial fins evenly spaced. Figure 8 shows the components of the hot water heater (without insulation). The heating assembly is 12-5/16 inches long, with the outer tube 3 inches in diameter and the inner tube (less the fins) 3/4 inch in diameter. The fins are 2.8 inches in diameter. The entire assembly is coated with 2 inches of Freon-blown polyurethane foam for insulation.

DISPENSING UNIT

The hot and cold water dispensing unit is shown in Figure 9. It consists of two dispensing valves and a hand pump mounted in an open front aluminum housing. Both valves are 1/8 ips polypropylene

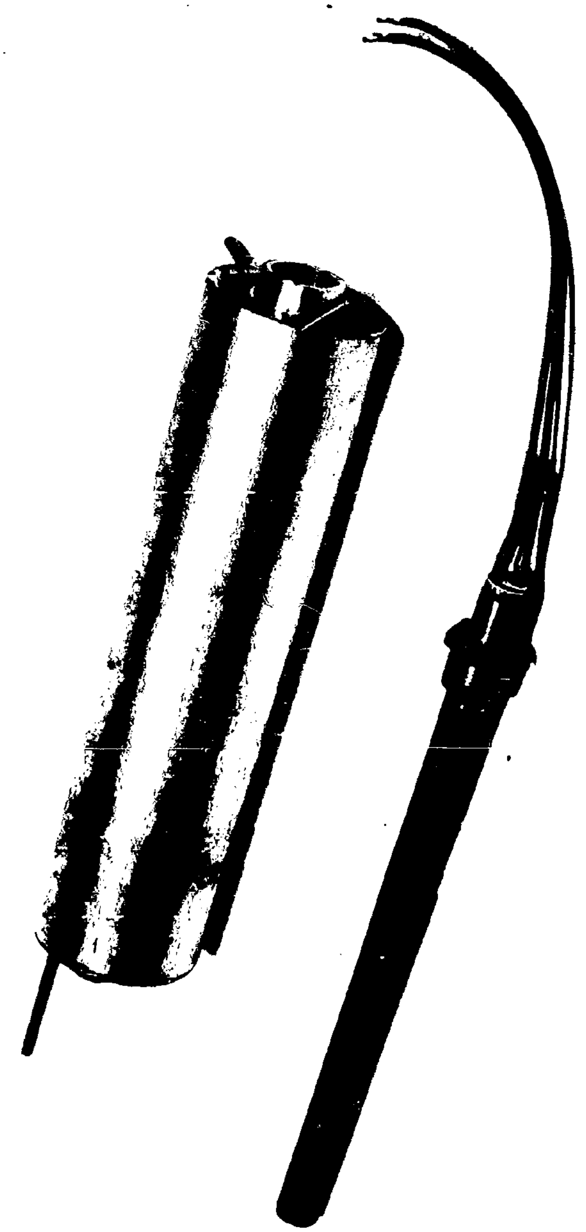


FIGURE 8 HOT WATER HEATER

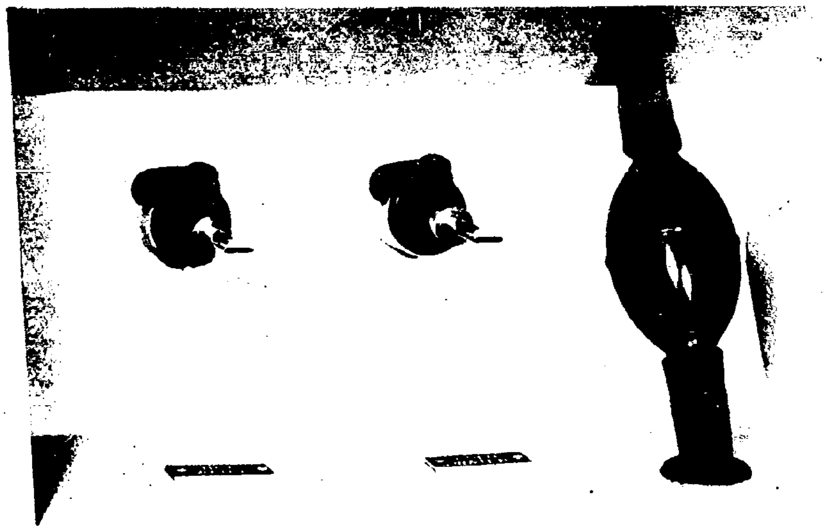


FIGURE 9 DISPENSING UNIT

valves. The hand pump is a flexible rubber bulb used to recirculate water through the hot water heater before drawing off hot water. The housing is 14-3/8 inches long, 9-3/8 inches wide, and 4-7/8 inches deep.

PARTICLE TRAP

The particle trap is located in the vapor line just upstream of the condenser. Its purpose is to remove minute wear particles originating in the compressor. The trap is disc shaped consisting of a 3-inch diameter by 1-inch cylindrical resin impregnated, ribbon-wound, cellulose filter enclosed in an aluminum shell. The vapor enters radially and exits axially. It is fitted with a drain for periodic cleaning. The trap is insulated with 1/2-inch plastic-rubber foam.

INSTRUMENTATION AND CONTROLS

The instrumentation and control system is designed for automatic, semi-automatic (manual start), and override operation. The graphic control panel is shown in Figure 10 and a wiring diagram of the system is shown in Figure 11.

Control Power

Referring to Figure 11, input power (28VDC) is connected to the plus (+) terminal of a small input subpanel at the upper left of the unit, when facing the panel front. The negative lead is connected to frame. By pushing in the SYSTEM ON button, SSL-5, relays PrR-6A and B pass power through fuses F1-A and B to the fuse buss and to vapor compressor fuse F-5, located on the input power control subpanel. Power reaching the fuse buss is signaled by the fused signal light in the SYSTEM ON button.

Vapor Compressor

Power passes through F-5 on the input power control subpanel to relay PrR-5 contacts whose coil is controlled by the switch-with-signal light SSL-2, shown as a pump symbol on the graphic panel. Feedback lamp illumination shows relay closure.

Two-step pump speed control is supplied by Motor Speed Control switch MSC-1, located in the center of graphic panel. A suppressor, SUPP-5, protects the contacts of PrR-5. Actual operating (normal) speed can be varied by means of rheostat, P-3, located under hot water heater.

Evaporator Heater Temperature Control

Meter relays with time delay relays used as interrupters are used in both heat control circuits (evaporator heater and hot water heater).

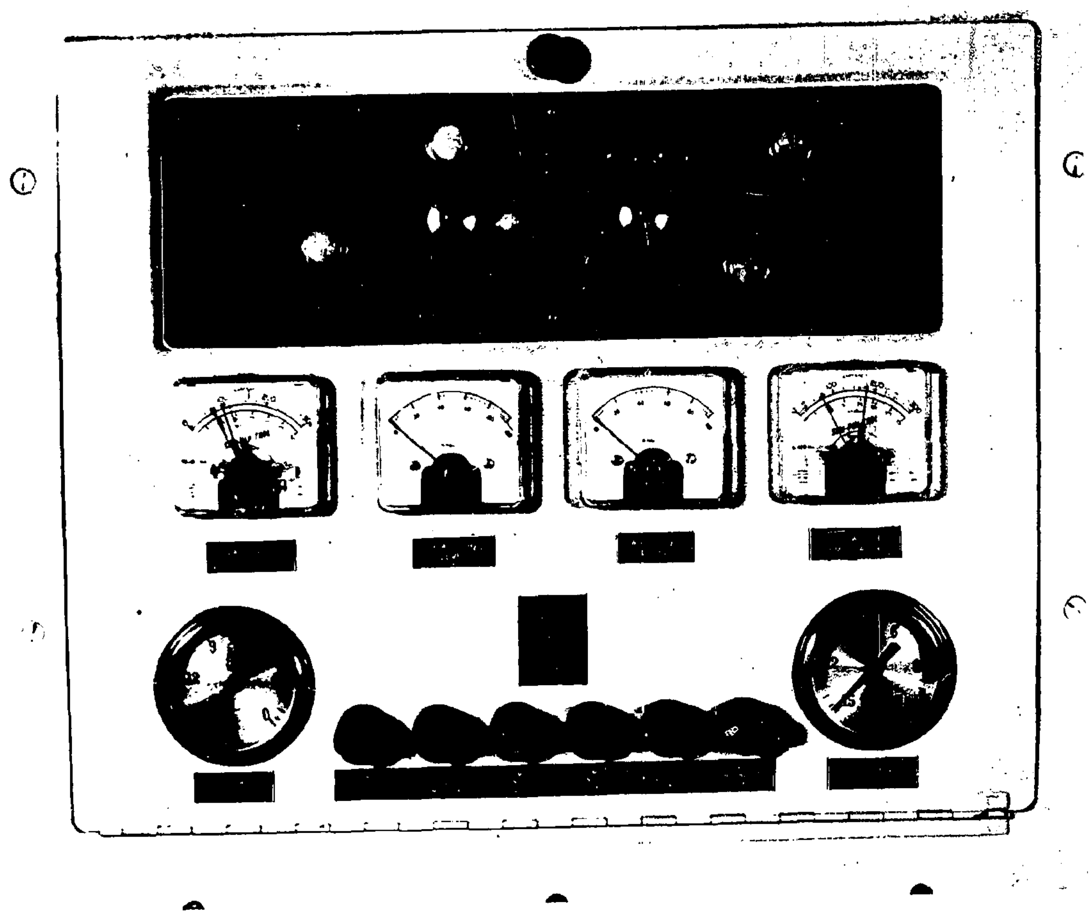
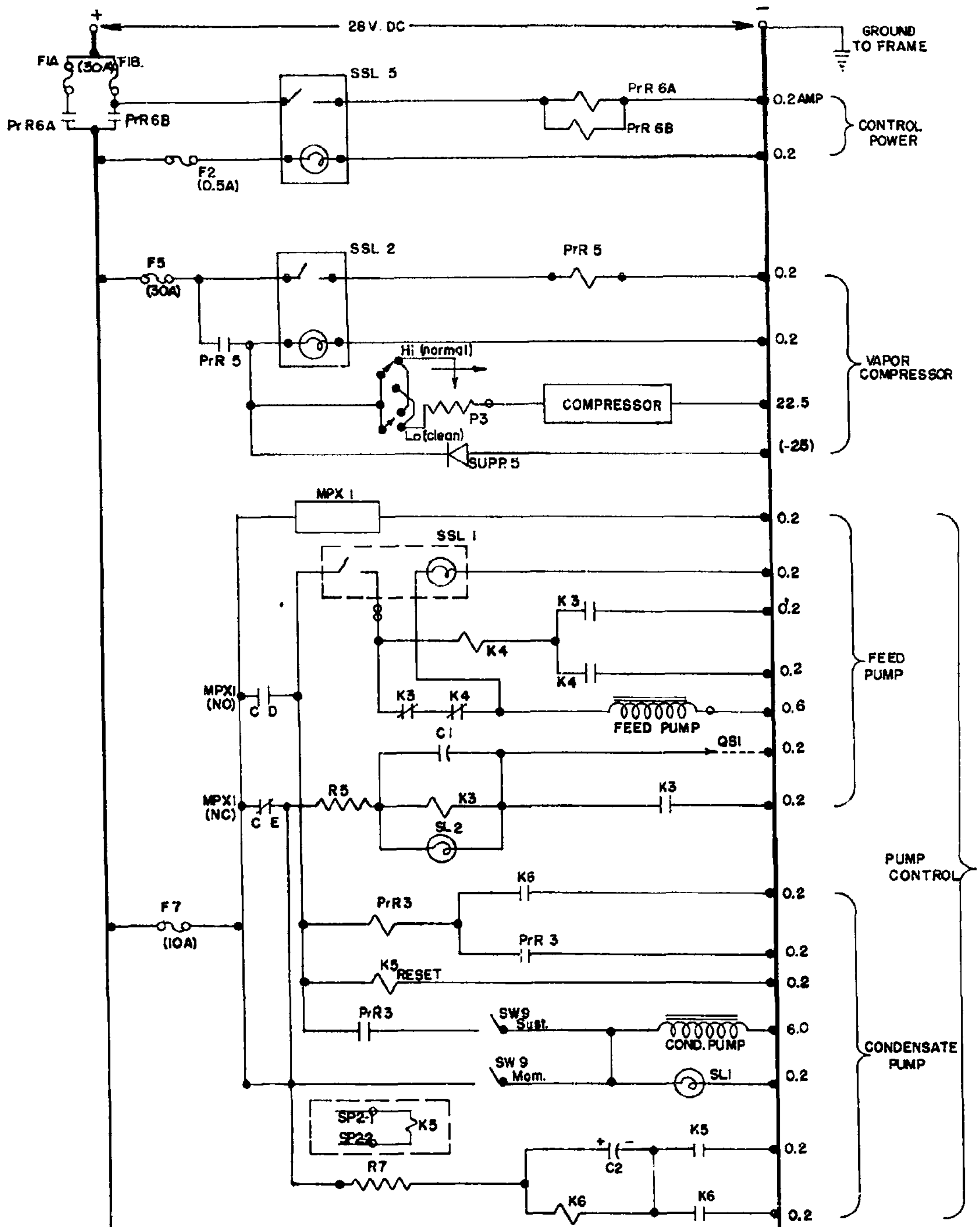


FIGURE 10 GRAPHIC CONTROL PANEL



SP2-1, SP2-2 are terminals for proposed condensate level probe

Figure 11A Wiring Diagram - Integrated Water Recovery System (Part I)

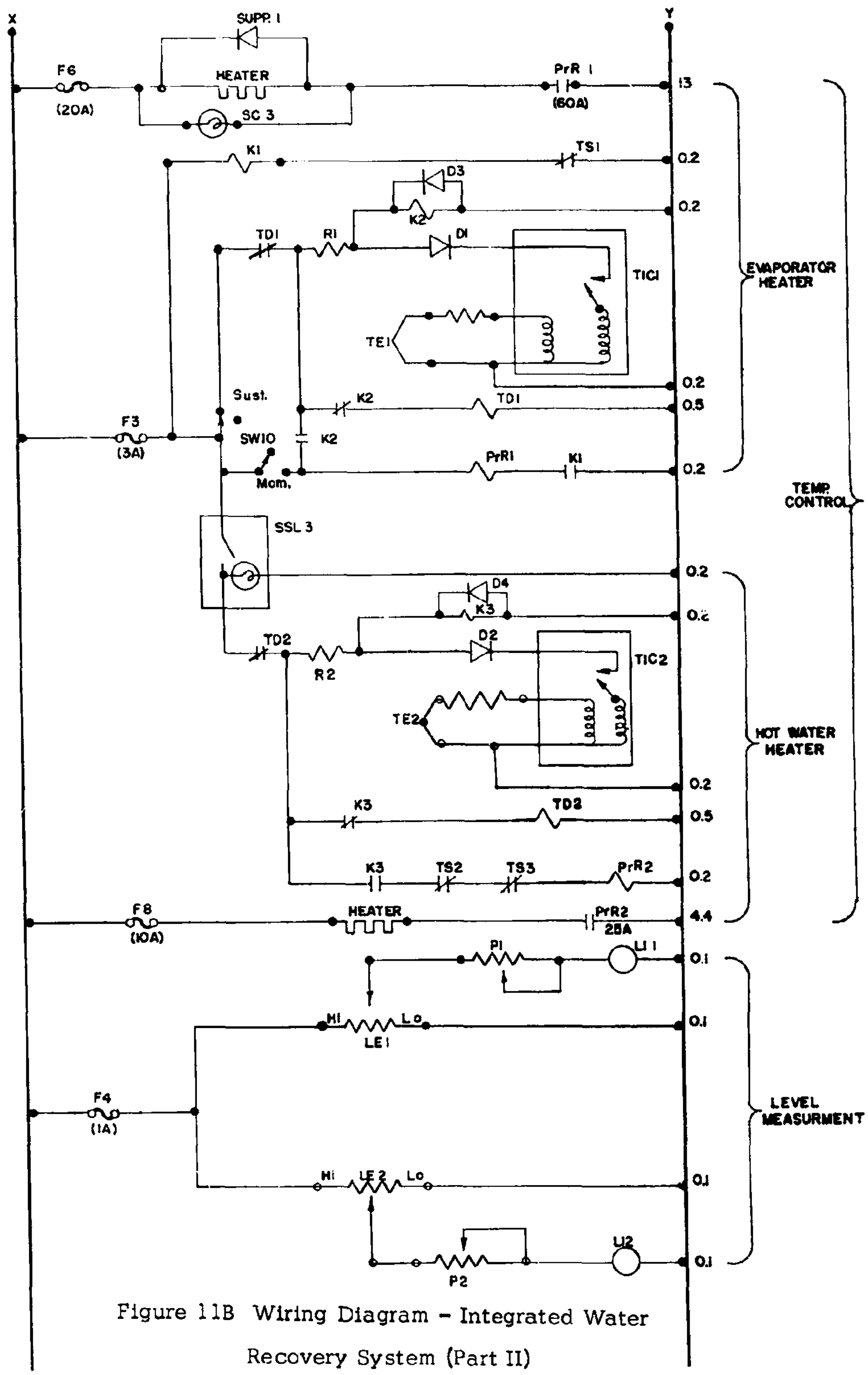


Figure 11B Wiring Diagram - Integrated Water Recovery System (Part II)

LEGEND FOR FIGURE 11

C	Capacitor
D	Diode
F	Fuse
K	Signal Relay
LE	Level Element
LI	Level Indicator
Mom.	Momentary
MPX	Motorized Program Switch
P	Potentiometer
PrR	Power Relay
QS	Quantity (Level) Switch
R	Resistor
SL	Signal Lamp
SP	Sub Panel (Terminal Point)
SSL	Switch with Signal Lamp
SUPP	Suppressor Diode
Sust.	Sustained
SW	Switch
TD	Time Delay Relay (Thermal)
TE	Thermal Element (Thermocouple)
TIC	Temp. Indicating Controller
TS	Temp. Switch

Temperature limit switch TS-1, located in the evaporator chamber, continuously energizes relay K-1. Relay K-1 allows the operation of power relay PrR-1 to energize the evaporator heater through fuse F-6. Power relay PrR-1 is energized as follows:

Thermocouple TE-1, located in the evaporator, senses water temperature by immersion. The resultant millivolt signal drives the pointer (and an accompanying contact) of the meter-relay TIC-1 upscale. When the measured temperature equals the desired setpoint, the contacts shown in TIC-1 close. On closure, a parallel path to pilot relay K-2 is obtained, allowing K-2 to drop out because of the increased voltage drop across resistor R-1. The second coil of TIC-1 has low resistance; it drives the pointer hard against the index.

Dropout of K-2 causes time delay relay TD-1 to start timing and power relay PrR-1 (controlling power to heater) to drop out. When time delay relay TD-1 times out, its contacts open, deenergizing all of the above circuitry. The pointer is allowed to drop away from the index if the temperature signal allows this. When TD-1 resets (thermally), relays K-2 and PrR-1 are again energized or, if temperature did not decrease, relay K-2 remains out keeping power from the evaporator heater.

Momentary override of heater control power is provided by the three-position toggle switch, SW-10. In the UP position, control is automatic; CENTER is off, and DOWN is manual heat. The switch has a spring return from the DOWN position. A suppressor across the heater protects relay PrR-1 contacts.

Hot Water Heater

The hot water heater system is turned ON by SSL-3 located on the graphic panel. On energizing, the operation of this heater is similar to the evaporator heater discussed above. Additionally, safety interlocks to power relay PrR-2 are provided by hot water limit switch TS-2 and hot water heater limit switch TS-3.

Pump Control

Both the feed and condensate pump control systems are fused through F-7, and both employ a common motorized switch, MPX-1, for timed, pulse control.

Feed Pump

The motorized switch, MPX-1, operates continuously, closing contacts CD (and opening contacts CE) once every 5 seconds for a 1-second duration. Pulsating power reaches pilot relay, K-3, 4 seconds out of 5, if QS-1 is closed. (QS-1 is a carbon electrode, shorted to ground by high urine level in the evaporator.)

Relay K-3, with the assistance of capacitor C-1 and resistor R-5, delays opening when the motorized switch, MPX-1, contact closure shifts from CE to CD. Contacts CD of the motorized switch, MPX-1, energize the pilot relay, K-4, through delayed contact of K-3 and the Feed Pump pushbutton, SSL-1. For this 1 second (period of closure of the MPX-1 contacts CD), relay K-4 locks itself.

The feed pump is not pulsed by contacts CD, because first K-3 and then K-4 contacts serially open. This is because of high urine level, which started the sequence. If QS-1 had not shorted, the feed pump could have been pulsed through K-3 and K-4 closed contacts.

<u>Condensate Pump</u>

On closure of the motorized switch, MPX-1, contacts CE, relay K-6 locks itself in by K-5. Again by time delay of K-6, power relay PrR-3 locks in on closure of contacts CD, energizing the condensate pump through switch SW-9 located on the graphic panel. The pump can be manually pulsed by pressing DOWN, SW-9.

Meter relay K-5 is periodically reset by its reset coil each time the pump is pulsed.

Signal light SL-1 on the control panel signals operation of the condensate pump.

<u>Level Measurement (Storage Tanks)</u>

Each of the storage tanks drives a multiturn potentiometer, attached to the constant tension springs, which through fuse F-4 drives a voltmeter calibrated in % level. Calibration rheostats are provided on the relay panel for initial calibration.

<u>Miscellaneous Instrumentation</u>

Two mechanical measurements of pressure are provided - evaporator pressure and condenser pressure. The pressure gauges are actually vacuum gauges, provided with reverse scales, such that absolute vacuum reads 0 and atmosphere pressure reads 14.7.

TEST OPERATIONS

COMPONENT TESTS

Upon completion of the integrated water recovery system, all components were tested individually and in combination when necessary to assure proper operation. Modifications were made as needed and operating characteristics were documented.

Water Storage Tanks

The water storage tanks were checked for volume, constant tension spring pressure, output flow rates, and leakage. The "% Full" meters were calibrated and an optimum procedure for external filling was determined. The results of this check out are as follows:

	Waste Water Tank	Potable Water Tank
Volume	8.1 liters	8.1 liters
Constant Tension Spring Pressure	0.6 psi	1.2 psi
"% Full" meters	80ml/1%	80ml/1%
Leakage	0	0
Output flow (at 6 ft)	does not apply	satisfactory

The addition of liquids to the storage tanks through the "fill" valves is facilitated by first neutralizing the constant tension spring pressure. This eliminates the need to push the liquid against the constant tension spring pressure.

Evaporator-Condenser

The rotating evaporator-condenser was checked for proper rotational speed, adequate sealing of the covers, orientation of liquid on the evaporator surface and operation of the temperature indicators, the heater control, the radiant heater, and the level sensor. (Performance of these components working together was investigated as part of the process testing.)

Vapor Compressor

The vapor compressor was tested for proper rotational speed, capacity both in regards to flow rate and pressure differential, the effect of voltage fluctuations and operating temperature. Throughout the entire test program the compressor was checked for wear and for behavior during start-up and shutdown of the system. The compressor's capacity was checked at atmospheric pressure and at the unit operating pressure with air. The compressor delivered 1.63 ft^3/min. of air at a ΔP of 0.6 psi and a rotational speed of 1270 rpm.

It should be noted that during the entire test program, the vapor compressor was operated for a total of about 200 hours.

Feed Metering Valve

The feed metering valve was checked for proper delivery rate and operation under system operating conditions. The original pump, consisting of a solenoid-operated spring-returned plunger and two check valves, was found to be inadequate for the system. The solenoid was too small to both load the spring and pull against the ΔP caused by ambient pressure. The check valves would not operate properly when sufficiently strong springs were used to hold back the feed liquid when the pump was not stroking. This pump was, therefore, replaced with the 3-port 2-way solenoid valve and the collapsible liquid chamber. This new pump has a very accurate and repeatable delivery rate and a high degree of reliability. The delivery rate can easily be adjusted from 1 ml/min. to 30 ml/min.

Condensate Pump

The condensate pump was checked for delivery rate, and its ability to pump from system operating pressure into the potable water storage tank.

Urine and Distillate Filters

These filters were checked for leakage and for liquid flow through them. Both filters sealed well; the feed and condensate pumps had no difficulty pumping water through them at designed rates. It was found that to operate the distillate filter efficiently under laboratory conditions it was necessary to reorient it 180° Upon making this change it was necessary to add a felt pad in the inlet end of the filter to prevent particles of charcoal from falling back into the liquid line.

Heat Exchangers

The heat exchangers were individually checked for leakage and pressure drop. No leakage was found and the pressure drops across them were negligible. Efficiencies and temperature differentials across them were investigated as part of the process testing.

Hot Water Heater

The hot water heater was checked for leakage, heater operation and control, and temperature increase of the liquid. The heater was found to have no leaks, the heater and control system gave an effluent liquid temperature at 170°F with no difficulties.

Dispensing Unit

The dispensing unit was checked for proper operation. The potable water storage tank delivered water to the cold water tap 6 feet from the unit. Water was recirculated through the hot water heater with the hand pump and hot water was drawn off at the hot water tap. All operations were satisfactory with no difficulties encountered.

Instrumentation and Controls

Each control system and indicator was checked under operating conditions after each component of the system had been checked out. The sequence timer pulsed the feed pump and condensate pump 1 second out of every 5 seconds. The high level sensor sensed high level satisfactorily and cut the feed metering valve out of the circuit as designed. The heater control controls the heater circuit to maintain the desired temperature, though it was necessary to electrically insulate the heater control sensing thermocouple from the evaporator liquid. Electrical interference from the high level probe rendered the heater control useless. Proper operation was obtained with the insulation. The on-off switches for power and for the evaporator compressor worked satisfactorily and all manual overrides functioned properly.

PRELIMINARY PROCESS TESTS

With all individual components of the system operating satisfactorily, the preliminary process testing was conducted in three basic phases:

1. Batch operation.
2. Continuous feed operation with fresh water.
3. Continuous feed operation with waste water (urine-wash water mixture).

The batch operations were used to determine optimum liquid levels in the evaporator, compressor characteristics during the transition from no evaporation to evaporation, and integrating of the instrumentation probes. It was determined that the evaporator should operate with approximately 50 ml of liquid. The liquid level sensor is capable of maintaining this volume to ± 5 ml. It was also determined that with 100 ml or more in the evaporator, the evaporation rate decreased significantly.

The liquid was heated to boiling with the makeup radiant heater and controlled by the temperature control thermocouple in the liquid and the indicating meter relay on the control panel. During heat up, the compressor maintained a 0.7 psi ΔP between the evaporator and condenser; during evaporation the evaporator pressure rose slightly, thus requiring a change in the temperature control set point. However, this change can be compensated for by initially setting the temperature controller for the boiling temperature corresponding to the higher pressure.

Before proceeding to the next phase of testing, air leakage into the system was checked. It was determined that this air-in leak rate was only 0.2 to 0.4% of the designed water vapor flow rates.

The second phase of the preliminary process testing consisted of running the system while continually feeding in fresh water. For this phase of testing, temporary temperature probes were installed at important locations in the system. These temperatures were recorded on a recording potentiometer. Salt (NaCl) was added to the evaporator to give the water a significant conductivity necessary for the operation of the level sensor.

During this phase of testing, operating characteristics were determined and documented for various modes of operation, start-up and shutdown procedures were perfected, and modifications to improve performance were incorporated into the system. The results of the various aspects of the testing are summarized below.

Effect of Inlet Liquid Feed Temperature

The system was run feeding liquid in at various temperatures. These were cold feed (room temperature), feed from the heat economizer (about 120°F), feed at or near its boiling point (160°F), and liquid at temperatures above its boiling point (with up to 4% flashing upon entering the evaporator).

Introducing the feed liquid at or near its boiling point gave the best results. To bring the liquid from the heat economizer up to this temperature the second stage heat exchanger was added to the system using the excessive superheat from the compressed vapor as a source of heat. This method has the added advantage of introducing the vapor to the condenser surface at its saturation temperature.

Effect of Condenser Area Configuration

The condenser area was designed with the compressed vapor entering the annulus from the rear, directed along the condensing surface parallel to its axis.

The vacuum vent line is located at the center of the front cover. With this configuration the vapor "channeled," that is, most of the vapor passed between the 4 o'clock and 8 o'clock positions, thus not fully utilizing the condensing surface. As a result, vapor which was unable to condense was swept into the vacuum vent line. This uncondensed water vapor was collected in an ice water cold trap before the vacuum pump. At a liquid feed rate of 6 ml/min., approximately 35% of the water was collected in the cold trap.

The condenser area and condensing surface were modified to prevent the vapor "channeling." The single port vapor inlet line was modified by the addition of a coil concentric with the rotating evaporator-condenser (see Figure 4) allowing the vapor to enter the condenser area through several small ports impinging directly on the condensing surface along its entire circumference. The condensing surface was also modified by the addition of a helical wire coil. This coil allows the rotating condensing surface to act as a pump, throwing the vapor toward the rear away from the vacuum vent line, and thus getting complete distribution of vapor over the entire condensing surface. As a final barrier to prevent vapor from being lost to the vacuum vent line, the front cover was modified to have cooling water pass through it, thus condensing any vapor which might be swept out by the non-condensable gases. Operation of the unit with this configuration resulted in less than 1% of the water vapor being lost through the vacuum vent.

General

With the modified system continuous, semi-automatic operation of the system proceeded with little difficulty. A series of tests were run at various pressures and corresponding temperatures. Optimum results were obtained at pressures slightly higher than design. The system was designed for an evaporator pressure of 4.7 psia and a condenser pressure of 5.2 psia. Optimum results were obtained at an evaporator pressure of 5.2 psia and a condenser pressure of 5.7 psia. At these conditions the system delivered an average of 5.7 ml/min. with peak delivery rates over 15-minute increments of 10 ml/min.

For starting up the system and shutting it down, it was necessary to add a by-pass line between the evaporator and condenser. This prevents large ΔP's from existing across the compressor blades during transient conditions going down to vacuum and bleeding back up to ambient pressure.

The third phase of the preliminary test program consisted of feeding a mixture of urine and wash water to the system and operating continuously. This phase allowed verification that the procedures developed with fresh water were adequate for waste water operation and modification of the procedure if necessary. From this phase, the potability of the effluent condensate after post treatment was determined, odor control was investigated, and the cleaning procedure verified. A modification of the shutdown procedure also evolved from this test series.

During operation, it was necessary to periodically increase the heater control relay set-point by about 1°F because of the increased boiling point of the concentrated residue liquor. There was no odor detectable during operation of the system. Actual shutdown of the system made it clear that the initial shutdown procedure required modification to prevent residue sludge from backing up into the feed line. Back up took place while the system was being bled to ambient pressure. Modification of the procedure was also necessary in order to remove excessive odors before opening the front covers.

The shutdown procedure which was developed during the test program results in only a small amount of odor during cleaning and a residue of proper consistency for cleaning with the designed cleaning unit.

FINAL SYSTEM OPERATION

With all modifications made and using the operating techniques developed in the preliminary test, the final system operation tests were undertaken. Details of the operating conditions and test results are presented in Tables I and II. The system produced an average of approximately 6 ml/min. of water for periods of 4 to 5 hours with peak production for 15-minute increments of up to 10 ml/min. Analysis of the water showed it to be within the U.S. Public Health standards for potable water (Reference 3).

All components of the system, with the exception of the storage tanks, were used for the test. The storage tanks operated properly with fresh water but were not used in the waste water runs. It was deemed desirable not to contaminate the waste water tank with urine before shipment, therefore the potable water was collected in graduated containers instead of the potable water storage tank for the purpose of measuring the output flow rate.

The urine and wash water treated with 1% potassium persulfate was fed through the detritus filter from a 4-liter plastic container. The wash water used contained 500 ppm benzalkonium chloride as a detergent. The feed pump metered the waste water mixture into the system at a rate of 6 ml/min. This flow rate caused the high level probe to occasionally stop the feed pump. The waste water entered the heat economizer at about 60°F and exited at about 120°F. This liquid then entered the second stage feed heater where it was heated to its boiling point by the superheated compressed vapor. From there it entered the evaporator. The compressor was operated at a nominal speed of 1060 rpm.

The compressed vapor from the compressor passed through the second stage feed heater and into the condenser, operating at 5.7 psi, at its saturation temperature where it was condensed. The condensate was drawn off through the heat economizer by the condensate pump. The condensate then passed through the final filter into the graduated collection container. The filter contained activated charcoal, monobed ion-exchange resin, and a bacterial filter. All the condensate collection receptacles and collection lines were sterilized. The water collected was analyzed for potability.

After operating for 4 to 5 hours, the system was shut down and cleaned according to the procedure developed in preliminary tests. This procedure proved to be very satisfactory, resulting in only a minimum of odor being given off upon opening the front covers and the residue being of the proper consistency for cleaning.

TABLE I

ANALYSIS OF RECOVERED WATER - PRELIMINARY RESULTS

Feed Composition: 50% urine; 50% wash water containing 500 ppm BAC, 1% $K_2S_2O_8$ added.

Final Filtration: Type OL charcoal.
IR-120 cationic ion-exchange resin (H form).
Millipore bacterial filter.

	Before Filter	After Filter
Sediment	very slight	none
Turbidity	very slight	none
Odor	very slight	none
$SO_4^{=}$ (Note 1)	negative	negative
Cl^- (Note 2)	negative	negative
NH_3 (Note 3)	positive	negative
pH	8.3	7.0 (Note 4)
Coliform Count (Note 5)	none	

(1) Barium chloride test solution.

(2) Silver nitrate test solution.

(3) Nessler's Reagent.

(4) Initially 3.6. Additional treatment with anion resin gave pH of 7.0.

(5) Membrane filter technique, Standard Methods for the Examination of Water and Wastewater. 11th Edition, American Public Health Association.

TABLE II

ANALYSIS OF RECOVERED WATER - FINAL RESULTS

Feed Composition: 50% urine; 50% wash water containing 500 ppm BAC, 1% $K_2S_2O_8$ added.

Final Filtration: Type KE-1 charcoal.
MB-1 monobed ion-exchange resin.
Millipore bacterial filter.

	Before Filter	After Filter	Public Health Std. (Not to exceed) (Note 1)
Sediment	very slight	none	no standard
Turbidity	slight	none	5 units
Odor	present	none	Threshold odor no. of 3
$SO_4^{=}$	negative	negative	250 ppm
Cl^-	negative	negative	250 ppm
NH_3	positive	negative	no standard
pH	8.3	7.0	no standard
Conductivity (micromhos/cm)	95	13	no standard
Total Dissolved Solids (ppm)	85	15	500
Total Nitrogen (Note 2) (ppm)	0.25	0.07	45 ppm as nitrate
Color (units)	40	10	15
Plate Count per ml (Note 3)	1000	1	no standard
Coliform per 100 ml	none	none	1
COD (ppm) (Note 4)	150	50	no standard

(1) "Public Health Service, Drinking Water Standards." 1962 (Ref. 3).

(2) Kjeldahl method.

(3) Membrane filter technique.

(4) Chemical Oxygen Demand, Standard Methods for Examination of Water and Waste Water. (Tap water gave 170.)

The system's maximum power consumption with all components on (including hot water heater, radiant make-up heater and solenoid pumps) was 0.89 kw. Major contributors were power losses in the speed control rheostat (approximately 0.3 kw) and mechanical losses in the speed reduction gear train and the shaft seals. The former loss could probably be eliminated by utilizing a 400-cycle, a-c power source. Time did not permit an evaluation of this subject.

SUMMARY AND CONCLUSIONS

The vapor compression distillation cycle, as used in the Integrated Water Recovery System, is capable of producing potable water from urine and wash water at approximately the desired rates. Residue in the system can be cleaned periodically with no problems of undesirable odors if the recommended procedure is employed.

The system was fed with a 50/50 mixture of urine and wash water (containing 500 ppm BAC as a detergent) treated with 1% $K_2S_2O_8$. The condensate was filtered through a charcoal ion-exchange resin-bacterial filter. The effluent water was tested for inorganic contamination, organic contamination, bacterial contamination, odor, taste, and other properties such as pH and conductivity. In all categories, the effluent water was within the U.S. Public Health Service standards for potable water. (Reference 3.)

RECOMMENDATIONS FOR ADDITIONAL STUDY

In the course of testing the Integrated Water Recovery System, many modifications and improvements were made. However, as with any prototype system, this test program also revealed areas for additional study or improvement that should be considered for a "Model II" system. Time did not permit complete resolution of all of these points. The recommendations are summarized below.

1. <u>An Improved Pressure-Temperature Control System</u>

   Variations in the boiling point of the evaporator liquid due to changes in pressure and the increased concentration of the residue should be automatically compensated for in the heater temperature control system. This would greatly improve the efficiency of the system.

2. <u>Condensate Level Sensor</u>

   An active rather than a passive level sensing probe appears to be necessary for satisfactory operation. Two types should be considered. The first is of the heat conductivity type where the difference in resistance of two precision resistors, due to temperature difference caused by the heat carried away by the vapor phase and by the liquid phase in the condenser, would indicate liquid level.

   The second type would employ a mechanically vibrating reed, the vibrations of which would be damped by increasing liquid level. Measurement of the damping effect would indicate liquid level.

3. <u>Column Insulation</u>

   The central column in the evaporator should be enclosed in a plastic tube (such as melamine) which would effectively insulate electrical terminals from being grounded or shorted by salt deposits.

4. <u>Shaft Seals</u>

   All shaft seals should be enclosed in stainless steel housings. Such housings are specialty items and not off-the-shelf items.

5. <u>Condensate Pump</u>

   A positive displacement condensate pump should be developed which would be completely self-priming and would not be subject to check valve fouling. Such a pump, although heavier than the solenoid pump now in use, would present advantages which would more than compensate for the loss of the lower hardware weight.

6. Condensate Filter

The aluminum condensate filter was originally designed to contain only charcoal. With the addition of ion-exchange resin, consideration should be given to fabricating the housing from a metal, such as stainless steel, or from a plastic material.

7. Gear Lubrication

An expansion chamber should be added to the lubrication vent on the gear box to compensate for thermal expansion in the gear housing under zero gravity conditions. The present standpipe is adequate for laboratory testing but a bellows-type chamber may be required for weightless conditions.

8. New Modifications

Some modifications on the system were made late in the test program. These were not necessarily of optimum design due to the lack of time remaining until shipment of the system. Modifications include the instrumentation probe in the evaporator and the motor speed control rheostat. The instrumentation probe should be completely housed in a metal sleeve and the rheostat should be light weight.

9. Compressor Design

Further consideration should be given to the use of a centrifugal compressor operating at a suction pressure of about 0.5 psia. Operation at such pressures requires a smaller ΔP across the compressor in order to obtain the desired vapor temperature increase. A compressor of the type suggested is not an off-the-shelf item and would require a design and development program.

10. Residue Incineration

Consideration should be given to a high-temperature design of the evaporator-condenser assembly so that the residue can be incinerated in place and removed without opening the evaporator.

11. Water Pretreatment

Additional testing should be done to determine the necessity of adding an oxidizing agent to the feed urine. It is anticipated that the recovered water will be of slightly lower quality but will still be potable.

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